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## WHAT NEW PHYSICS CAN DOUBLE BETA DECAY EXPERIMENTS HOPE TO SEE?

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### ABSTRACT

Double-beta decay experiments have been traditionally interpreted in terms of the Gelmini-Roncadelli triplet majoron model which has since been ruled out by the LEP data on the  $Z$  resonance. We therefore systematically re-examine the kinds of physics to which double-beta decay experiments might be sensitive, with particular attention paid to a potential scalar-emitting mode. We find six broad categories of models, including some new categories which have not been previously considered. Models in these new classes robustly differ from the old ones in the electron energy spectrum that they predict, and depend on different nuclear matrix elements. For models in which the electron neutrino mixes with sterile neutrinos, an observable double-beta decay signal typically implies a sterile-neutrino mass in the neighbourhood of 1 MeV to 1 GeV.

### 1. Introduction

Over the past five years double-beta-decay experiments have come of age. Since the first direct observation of Standard-Model neutrino-emitting double beta decay ( $\beta\beta_{2\nu}$ ) was made several years ago,<sup>1</sup> other experimenters have taken up the challenge and have observed this decay in several elements.

Much of the original motivation for these experiments was not so much to find these expected Standard-Model decays, but rather to search for nonstandard  $\beta\beta_{0\nu}$  decays in which the two outgoing electrons are unaccompanied by neutrinos. Such a

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decay must violate the conservation of electron number,  $L_e$ , and as such would be a smoking gun for ‘new physics’ from beyond the Standard Model. The possibility of breaking electron number spontaneously also motivated searching for a third decay,  $\beta\beta_\varphi$ , in which the electrons emerge together with the appropriate Nambu-Goldstone boson, called the majoron. Both of these decays were indeed predicted<sup>2,3</sup> by a simple and elegant model, due to Gelmini and Roncadelli,<sup>4</sup> in which lepton number was spontaneously broken by an electroweak-triplet Higgs field. Although this model has since been ruled out by the observations at the  $Z$  resonance at LEP, it has still remained as the paradigm against which double-beta-decay experiments compare their results.

Interest in understanding the kind of physics to which these experiments can be sensitive was recently revived by the tentative observation of an excess of electrons near, but below, the endpoint for the decays of  $^{100}\text{Mo}$ ,  $^{82}\text{Se}$  and  $^{150}\text{Nd}$ , with a statistical significance of  $5\sigma$ .<sup>5</sup> This observation echoed earlier indications for such an excess in the decay of  $^{76}\text{Ge}$ ,<sup>6</sup> although this earlier evidence was later ruled out both by the initial investigators, as well as by others.<sup>7</sup> Hints of excess events also persisted in the  $^{76}\text{Ge}$  data<sup>8,9</sup>, although at a tenth or less of the originally-detected rate. Although, at present, most of the anomalous events reported by the Irvine group seem to be due to resolution problems for the higher-energy electrons,<sup>10</sup> there remains a smaller set of residual events whose magnitude is consistent with observations from other experiments.<sup>11,12</sup>

This experimental activity has provoked a theoretical re-examination<sup>13,14,15,16</sup> of the kinds of new physics that could be expected to be detectable with the current sensitivity of  $\beta\beta$  experiments. In particular, attention has been devoted to understanding the implications for these experiments that can be extracted from the spectacular experiments at LEP. The principal idea is to evade the LEP bounds by forbidding any coupling between the  $Z$  boson and any new light degrees of freedom which appear in the model. This is most naturally ensured by making all such new particles electroweak singlets, generalizing the old singlet-majoron model.<sup>17</sup> The purpose of this article is to summarize the results of this re-examination. The general conclusion can be encapsulated by the statement that double-beta decay can be generated at an observable level, but only if the new physics has rather different properties than have previously been assumed.

## 2. General Properties of Double Beta Decay

For the purposes of classification it is convenient to write the rates for double-beta decay in the following way:<sup>14,16</sup>

$$d\Gamma(\beta\beta_i) = \frac{(G_F \cos \theta_C)^4}{4\pi^3} |\mathcal{A}(\beta\beta_i)|^2 d\Omega(\beta\beta_i), \quad (1)$$

where  $G_F$  is the Fermi constant,  $\theta_C$  the Cabibbo angle,  $\mathcal{A}(\beta\beta_i)$  a nuclear matrix element, and  $d\Omega(\beta\beta_i)$  the differential phase space for the particular process. The index ‘ $i$ ’, in  $\beta\beta_i$  represents the possible decays  $\beta\beta_{2\nu}$ ,  $\beta\beta_{0\nu}$ ,  $\beta\beta_\varphi$  etc.

From eq. (1) one can see there are two quantities to which double-beta-decay experiments are sensitive. They are:

**1. The Electron Energy Spectrum:** This quantity is the relative frequency of the observed outgoing electrons, as a function of their energies,  $\epsilon_k$  ( $k = 1, 2$ ). To

a good approximation (a few percent) the *shape* of this distribution is completely described by the factor,  $d\Omega(\beta\beta_i)$ , of eq. (1), and is therefore completely independent of the uncertainties that are associated with the nuclear matrix elements. This is because the maximum energy,  $Q \sim (1 - 3)$  MeV, that is released by the decay is much smaller than the typical momentum transfer,  $p_F \sim 100$  MeV, between the decaying nucleons that sets the scale for the momentum dependence of the nuclear matrix elements.

For  $\beta\beta_{0\nu}$  decay,  $d\Omega(\beta\beta_{0\nu})$  is given by

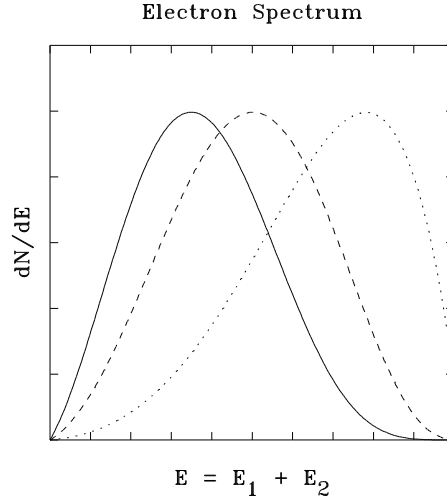
$$d\Omega(\beta\beta_{0\nu}) = \frac{1}{64\pi^2} \delta(Q - \epsilon_1 - \epsilon_2) \prod_{k=1}^2 p_k \epsilon_k F(\epsilon_k) d\epsilon_k. \quad (2)$$

Here  $p_k = |\mathbf{p}_k|$  is the magnitude of the electron three-momentum, and the endpoint energy,  $Q$ , for the electron spectrum is given in terms of the energies of the initial and final nuclear states,  $M$  and  $M'$ , and the electron mass,  $m_e$ , by  $Q = M - M' - 2m_e$ . Finally,  $F(\epsilon)$  is the Fermi function, normalized to unity in the limit of vanishing nuclear charge. The corresponding quantity for the other processes has a similar form,

$$d\Omega(\beta\beta_i) = \frac{1}{64\pi^2} (Q - \epsilon_1 - \epsilon_2)^{n_i} \prod_{k=1}^2 p_k \epsilon_k F(\epsilon_k) d\epsilon_k. \quad (3)$$

(The above formula applies to the scalar-emitting decays provided that the emitted boson is massless. Should it have mass  $m$  then the factor  $(Q - \epsilon_1 - \epsilon_2)$  should be replaced by  $((Q - \epsilon_1 - \epsilon_2)^2 - m^2)^{1/2}$ .)

It is only the *spectral index*,  $n_i$ , which differs depending on the type of decay, and whose implications for the spectral shape are detectable experimentally. The standard  $\beta\beta_{2\nu}$  decay has  $n_{2\nu} = 5$ , and the resulting spectral shape may be compared with the cases  $n = 1$  and  $n = 3$ , which arise in all other practical examples, in Fig. 1.



**Figure 1**

*The electron energy spectrum corresponding to the spectral indices  $n = 1$  (dotted),  $n = 3$  (dashed) and  $n = 5$  (solid).*

**2. The Integrated Rate:** The other observable quantity is the *normalization*,  $\mathcal{A}(\beta\beta_i)$ , of the spectrum, as determined by the total rate for each of the possible types of decays. It is here that one encounters the uncertainties associated with calculating nuclear matrix elements. It is convenient to parameterize our ignorance of these matrix elements by writing them in terms of a model-independent set of form factors. The basic nuclear matrix element which determines the double-beta decay rates is<sup>16</sup>

$$W_{\alpha\beta}(p) \equiv (2\pi)^3 \sqrt{\frac{EE'}{MM'}} \int d^4x \langle N' | T^* [J_\alpha(x) J_\beta(0)] | N \rangle e^{ipx}, \quad (4)$$

where  $J_\mu = \bar{u}\gamma_\mu(1 + \gamma_5)d$  is the weak charged current that causes transitions from neutrons to protons, and  $|N\rangle$  and  $|N'\rangle$  represent the initial and final  $0^+$  nuclei in the decay.  $E$  and  $M$  are the energy and mass of the initial nucleus,  $N$ , while  $E'$  and  $M'$  are the corresponding properties for the final nucleus,  $N'$ . For the decays of interest the most general possible form for  $W_{\alpha\beta}$  is<sup>16</sup>:

$$\begin{aligned} W_{\alpha\beta}(p) = & w_1 \eta_{\alpha\beta} + w_2 u_\alpha u_\beta + w_3 p_\alpha p_\beta + w_4 (p_\alpha u_\beta + p_\beta u_\alpha) \\ & + w_5 (p_\alpha u_\beta - p_\beta u_\alpha) + iw_6 \epsilon_{\alpha\beta\sigma\rho} u^\sigma p^\rho, \end{aligned} \quad (5)$$

where  $u_\alpha$  is the four-velocity of the initial and final nucleus, and the six Lorentz-invariant form factors,  $w_a = w_a(u \cdot p, p^2)$ , are functions of the two independent invariants that can be constructed from  $p_\mu$  and  $u_\mu$ .

Since the literature — for which there are a number of excellent reviews<sup>18,19</sup> — tends to quote expressions in which the nuclear matrix elements have been evaluated in a particular model of the nucleus, it is useful to have expressions for these form factors using these models. For instance  $\beta\beta_{2\nu}$ ,  $\beta\beta_{0\nu}$  and some kinds of  $\beta\beta_\varphi$  decays involve only the combination  $W^\alpha_\alpha$ , which may be written using the closure and nonrelativistic impulse approximations<sup>16</sup> as  $W^\alpha_\alpha = w_F - w_{GT}$ , with:

$$\begin{aligned} w_F &= \frac{2i\mu g_V^2}{p_0^2 - \mu^2 + i\varepsilon} \langle\langle N' | \sum_{nm} e^{-i\mathbf{p} \cdot \mathbf{r}_{nm}} \tau_n^+ \tau_m^+ | N \rangle\rangle; \\ w_{GT} &= \frac{2i\mu g_A^2}{p_0^2 - \mu^2 + i\varepsilon} \langle\langle N' | \sum_{nm} e^{-i\mathbf{p} \cdot \mathbf{r}_{nm}} \tau_n^+ \tau_m^+ \vec{\sigma}_n \cdot \vec{\sigma}_m | N \rangle\rangle. \end{aligned} \quad (6)$$

Here  $\mu \equiv \overline{E} - M$  is the average excitation energy of the intermediate nuclear state,  $\mathbf{r}_{nm}$  is the separation in position between the two decaying nucleons,  $g_V \simeq 1$  and  $g_A \simeq 1.25$  are the vector and axial couplings of the nucleon to the weak currents, and  $\langle\langle N' | \mathcal{O} | N \rangle\rangle$  represents a reduced matrix element from which the nuclear centre-of-mass motion has been extracted.

### 3. A General Classification

Given the limited number of observables which are measured in double beta decay models, there are essentially two questions which qualitatively distinguish the signatures of all models which can produce observable  $\beta\beta$  decay. These are:

**Q1:** Is electron number,  $L_e$ , broken?

**Q2:** Are there light bosons in the model which can produce  $\beta\beta_\varphi$  decays?

If the answer to this second question should be ‘yes’, then two more questions are needed to distinguish the possibilities for  $\beta\beta_\varphi$  decay:

**Q2a:** Is the light particle a Goldstone boson?

**Q2b:** What are the light boson’s quantum numbers if electron number is conserved?

We consider here only the case of a light scalar boson, although a similar analysis for a vector particle follows similar lines.<sup>15</sup>

The implications of these questions to the two types of experimental signatures that are possible is summarized in Table I.

$L_e$		A New Scalar:	$\beta\beta_{0\nu}$	$\beta\beta_\varphi$	Spectral Index
IA	Broken	Does Not Exist	Yes	No	N.A.
IB	Broken	Is Not a Goldstone Boson	Yes	Yes	$n = 1$
IC	Broken	Is a Goldstone Boson	Yes	Yes	$n = 1$
IIA	Unbroken	Does Not Exist	No	No	N.A.
IIB	Unbroken	Is Not a Goldstone Boson ( $L_e = -2$ )	No	Yes	$n = 1$
IIC	Unbroken	Is Not a Goldstone Boson ( $L_e = -1$ )	No	Yes	$n = 3$
IID	Unbroken	Is a Goldstone boson ( $L_e = -2$ )	No	Yes	$n = 3$
IIE	Unbroken	Is a Goldstone boson ( $L_e = -1$ )	No	Yes	$n = 5$

**Table I**

*A list of alternatives for modelling double beta decay.*

Six broad categories of models emerge from an inspection of Table I.

1. The most conservative option is the first category — case IIA of the Table — which predicts no new physics to be seen in  $\beta\beta$  experiments.
2. The next most conservative case is case IA, which is distinguished by a potential  $\beta\beta_{0\nu}$  signal but absolutely no scalar-emitting decays. This implies the standard  $\beta\beta_{2\nu}$  electron spectrum away from the endpoint.
3. The next category contains two classes of models which can be indistinguishable from the point of view of  $\beta\beta$  experiments — IB and IC of the Table. (The only way these could be distinguished would be if, in case IB, the scalar mass were nonzero and appreciable in comparison to the electron endpoint energy,  $Q$ . ) This class — which includes the old Gelmini-Roncadelli model — predicts<sup>13,14,16</sup> the standard GR form for the electron spectrum in scalar decay (*i.e.* it has spectral index  $n = 1$ , and depends only on the matrix elements  $W_\alpha^\alpha$ <sup>16</sup>).

4. Case IIB of the table forms another class all by itself. It would only be clearly distinguished from cases IB and IC if  $\beta\beta_{0\nu}$  decay should be found to be nonzero, since this is absolutely forbidden in case IIB. If the scalar-emitting decay,  $\beta\beta_\varphi$ , should be detected without finding an accompanying  $\beta\beta_{0\nu}$  signal, then (for effectively massless scalars) cases IB, IC and IIB could not be distinguished simply by looking at the electron spectrum.

This is, at first sight, surprising since these categories differ in whether they break electron number, and in whether the light scalar is a Goldstone boson or not. After all, Goldstone bosons couple derivatively and this might be expected to be reflected in the predicted electron spectrum. The main point here<sup>14,16</sup> is that the present detection limit for  $\beta\beta_{0\nu}$  is so strong that it forces all of the  $L_e$ -breaking terms in cases IB and IC to be so small as to be irrelevant for  $\beta\beta$  decay. As a result, so far as the  $\beta\beta_\varphi$  signal is concerned, the predictions of the  $L_e$ -breaking models of cases IB and IC are for all practical purposes indistinguishable from those of the  $L_e$ -preserving models in IIB. They also depend on the usual matrix elements  $W^\alpha_\alpha$ .<sup>16</sup>

5. Next comes cases IIC and IID — models which are identical in their implications for  $\beta\beta$  experiments. They both predict an electron spectrum which is qualitatively different from that of the older GR model, producing electrons which are softer than those of the GR majoron-emitting decay, but which are harder than those of the Standard-Model  $\beta\beta_{2\nu}$  decay.

The reasons for this alternative spectrum differs for cases IIC and IID. For case IID, conservation of  $L_e$  and the condition that the emitted scalar be a Goldstone boson imply<sup>14,16</sup> that the scalar emission amplitude must be proportional to the scalar energy, and this implies the observed softening of the electron spectrum. (Models in this class also depend on different nuclear matrix elements, depending as they do on the form factors  $w_5$  and  $w_6$ .<sup>16</sup>) For case IIC conservation of electron number requires the emission of *two* scalars at a time. The additional scalar phase space is then responsible for the additional suppression of high-energy electrons. Although the original models of this type<sup>20</sup> are ruled out by the LEP data, alternative singlet-type models are also possible.<sup>21</sup>

6. The final category is class IIE, for which  $L_e$  is conserved, the light scalars are Goldstone bosons, and for which  $L_e = -1$ . In this case the spectrum is expected to be softened compared to the GR model by (i) two powers of  $(Q - E)$ , since the emitted particles are Goldstone bosons, and (ii) by two additional powers due to phase space since  $L_e$  conservation requires two bosons to be emitted at a time. The spectral index for this spectrum is therefore expected to be  $n = 5$ , although no models of this type have yet been constructed. This would make it indistinguishable in shape from the standard  $\beta\beta_{2\nu}$  decay.

#### 4. More Detailed Predictions

In order to know whether all of the options given in Table I are actually viable, it is necessary to compute representative models in each category. Only then is it possible to

check that the properties that are required for an observable  $\beta\beta$  signal are consistent with all other neutrino bounds. Prominent among these bounds is consistency with Big-Bang Nucleosynthesis, since any model with a light scalar coupling significantly to neutrinos can easily ruin the present understanding of the primordial origin of the light elements. Although such an analysis has been done<sup>13,16</sup> for models in categories IB, IC, IIB and IID, work is still in progress for cases IIC and IIE.

Some general features do emerge from these analyses, however. For instance, a very broad category of models introduces the coupling between the light scalar and the electron neutrino by mixing  $\nu_e$  with various species of sterile neutrinos,  $\nu_s$ . A general feature of all such models is the necessity of having a neutrino state with a mass at least as large as  $\sim 1$  MeV if an observable exotic  $\beta\beta_\phi$  rate is required.<sup>16</sup> This is because in such models the  $\beta\beta_\phi$  rate vanishes in the limit that all neutrinos are degenerate, since in this limit there need be no mixing between electroweak eigenstates. This implies, in particular, that for light neutrinos, the  $\beta\beta_\phi$  decay rate is always suppressed by explicit factors of neutrino masses divided by the nuclear-physics scales,  $p_F \sim 100$  MeV, that are relevant to  $\beta\beta$  decay. An experimentally observable rate therefore requires at least some neutrino masses that are at least of order a few MeV.

Another general feature concerns the understanding of why the light degrees of freedom in the model should be so light. In this regard models in classes IB, IIB and IIC are theoretically unattractive in that they must build in a light scalar mass completely by hand. (An equally small scale is also required for models in class IC, since although here the Goldstone boson is naturally massless, the absence of  $\beta\beta_{0\nu}$  decay requires a similarly small fine-tuning of the scale of  $L_e$  breaking.) In all of these models such a small scale is typically only possible if the scalar potential involves dimensionless self-couplings that are as small as  $10^{-14}$ . It is nevertheless sometimes possible to make these models natural in the technical sense.<sup>16,22</sup> Models in category IID (and presumably IIE) are much more appealing in this way since for them the scale of symmetry breaking can be orders of magnitude higher.

## 5. Conclusions

It is clear that  $\beta\beta$  experiments do provide a window on potential new physics, and in a way which fundamentally probes the validity of electron-number conservation. Viable models exist which can account for detectable signals in these experiments, without being in conflict with other data, such as the properties of the  $Z$  boson as measured at LEP. Most interestingly, however, the properties of these models can differ significantly from what would be expected based on the early model building of previous decades. In particular, perhaps the theoretically best-motivated new models predict an entirely different electron energy spectrum, which should be searched for in the data of the ongoing experiments.

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